Abstract. This paper describes a study to see whether consumption of farmed fish in the UK is radiologically significant. Farmed fish might contain enhanced levels of radioactivity since their diet is entirely fishmeal-based fish food. Fishmeal is produced from marine fish. Atlantic salmon and rainbow trout are the main fish species farmed in the UK for consumption, and a cross-section of fish farms in England, Scotland and Wales were sampled during 2001. Fish species and the geographical locations of farms were selected on the basis of UK production rates. Some of the farms were re-sampled a few months later to check for variability. Trout farms were selected with differing freshwater hardness to see if this affected radionuclide uptake. Differences between salmon reared on so-called ‘organic-based’ feeds and conventional feeds were also investigated. Farmed fish samples were analysed for $^{14}$C, $^{99}$Tc, $^{210}$Pb, $^{210}$Po and gamma radionuclides, and found to contain low levels of radioactivity. There were no significant differences between levels in salmon and trout. Many gamma radionuclides were undetectable, and many of the samples had concentrations of natural radionuclides at what may be considered natural levels. Unexpectedly, a number of fish samples had $^{210}$Po:$^{210}$Pb ratios which were less than 1. Since concentrations were low, estimated doses were also low with most of the doses due to $^{210}$Pb and $^{210}$Po. The study also evaluated radionuclide transfer factors, used in mathematical models, for the pathway from fishmeal-based feed to farmed fish. Significant differences were found between calculated values for salmon and trout, and for different radionuclides. Direct comparisons of radionuclide concentrations in farmed fish and fish feed samples suggest that some bioaccumulation of $^{137}$Cs from fish feed to fish may be occurring, but not for $^{14}$C. For $^{99}$Tc, $^{210}$Pb and $^{210}$Po, there would appear to be depletion rather than bioaccumulation.

1. Introduction

As part of its responsibilities for food safety, the Food Standards Agency (FSA) monitors radioactivity in UK foodstuffs and assesses the impact of radioactivity in food by calculating radiation doses to the public. Results are published annually, for example [1]. A study on radioactivity in fishmeal [2] indicated that farmed fish in the UK might contain enhanced levels of radioactivity, particularly $^{14}$C and natural $^{210}$Pb and $^{210}$Po, as a result of their diet of fishmeal-based food.

Fishmeal is a high protein feed produced by processing marine fish, and is used to supplement the food intake of a number of animal species including ruminants, poultry and fish. In the case of farmed fish, these are normally raised throughout their lives on fishmeal-based fish food, and there will be a consequent transfer of radioactivity from the fishmeal to the farmed fish. This radioactivity will ultimately reach consumers of farmed fish. Fishmeal used within the UK comes from a number of sources worldwide as well as being produced within the UK. As a result, the radioactivity in fishmeal and in fishmeal-based feeds varies, as may the subsequent levels in farmed fish.

The FSA commissioned the study reported here to measure levels of radioactivity in farmed fish and fishmeal-based fish food from a representative cross-section of fish farms in the UK. The results were used to assess doses to members of the public consuming farmed fish, to calculate factors for the transfer of radioactivity from fish feed to farmed fish, and to provide some insights into transfer mechanisms.
2. UK farmed fish industry

Fish farming within the UK for consumable species essentially comprises production of Atlantic salmon (Salmo salar) and rainbow trout (Oncorhynchus mykiss) which are reared for the table. There is some farming of other species such as brown trout (Salmo trutta), turbot (Scophthalmus maximus), Arctic char (Salvelinus alpinus), cod (Gadus morhua) and halibut (Hippoglossus hippoglossus). However, since Atlantic salmon and rainbow trout are the predominant farmed fish species consumed by the UK public, these were studied in this work. Fish farming of these two species in the UK represents an annual production of around 130,000 tonnes salmon and 11,000 tonnes trout. Most of the salmon is reared in Scotland though small size fish are also reared in England for subsequent maturing in Scotland, and a single salmon farm operates in Northern Ireland. About 350 farms produce consumable salmon in Scotland. For trout, annual production for consumption is around 6,000 tonnes in England and Wales, 4,000 tonnes in Scotland, and 1,000 tonnes in Northern Ireland. The numbers of farms producing consumable trout are approximately 100 in England and Wales, 60 in Scotland and 30 in Northern Ireland. A further 5,000 tonnes of rainbow trout are produced annually for re-stocking for angling and on-growing in the UK. Detailed statistics on fish farming are routinely published (e.g. [3] and [4]).

Throughout their lives, farmed fish are raised on fishmeal-based fish feeds. Different feed compositions are used according to the age, size and species, and there is a sophisticated variety of feeds available to fish farmers. These include different sizes of crumbs for fish fry, pellets for fingerlings and ‘on-growers’, feeds for different water temperatures and different feeds for brood fish. However, the mixes generally contain about 40 to 50% (w/w) fishmeal, together with wheat, Soya meal, corn product, minerals and vitamins. Trout are raised in fresh water and are usually harvested for consumption when 1 year old and weigh about 0.3 kg. Salmon are raised in fresh water until smolt size, then transferred to seawater for maturing. Consumable salmon are usually 2 to 3 years old and weigh 4 to 5 kg.

3. Sampling and analyses

3.1. Sample choice

On the basis of the production figures above, a representative cross-section of farms in the UK was selected. This comprised seven salmon farms and one trout farm in Scotland, two trout farms in England and one trout farm in Wales. In general, all of the farms used fish feed containing fishmeal from South America, Norway, Iceland and Denmark.

The locations of the Scottish salmon farms (Figure 1) were chosen to give a geographic spread around the coast of Scotland. No salmon farms are located down the east coast of Scotland, mainly because the seawater quality for salmon rearing is better elsewhere. A farm producing fish to Soil Association organic standards was also included for comparison with conventional methods. The single Scottish trout farm was chosen so as to be unaffected by potential run-off of Chernobyl-derived $^{137}$Cs from uplands.

The three trout farms in England and Wales (Figure 2) were chosen to provide different fresh water conditions since this may affect radionuclide uptake. Trout on the Swansea farm were reared in soft acidic water, those at the Wimborne farm in hard alkaline water, and those at the Tincleton farm in neutral to alkaline water. For comparison, the trout in the Scottish farm were reared in soft acidic water.

3.2. Sampling campaign

Samples of salmon and trout ready for human consumption were obtained from each of the 11 farms during July 2001. Each farm provided whole fish which were then filleted as for consumption prior to analysis. Each farm also provided a sample of the fish feed representative of that which the culled fish had been predominantly raised on.
During October to December 2001, a further set of samples was obtained from five of the farms to check for variability of results. These farms were selected on the basis of including trout from one of the three English and Welsh sites and trout from the one Scottish site, together with salmon from three of the seven Scottish sites. Analytical results obtained from the earlier sampling were also used to help the selection.

FIG. 1. *Map of sampling locations in Scotland*

FIG. 2. *Map of sampling locations in England and Wales*
### 3.3. Sample analysis

All samples were analysed for gamma emitting radionuclides, $^{14}$C, $^{210}$Pb and $^{210}$Po which the earlier study [2] had indicated might be radiologically significant for consumers of farmed fish. In addition, one set of Scottish salmon and fish feed samples was analysed for $^{99}$Tc since discharges of this radionuclide from Sellafield continue to be of particular interest in the marine environment.

The analytical methods used were those applied routinely for monitoring aquatic samples as part of the broader FSA programme [1]. They included high-resolution gamma spectrometry for gamma emitting radionuclides, and radiochemical separation followed by appropriate counting methods for the other radionuclides. These counting methods comprised alpha counting by alpha spectrometry for $^{210}$Po, beta counting by liquid scintillation for $^{14}$C, and beta counting by gas proportional detectors for $^{99}$Tc and $^{210}$Pb.

### 3.4. Analytical results

The analytical results are summarised in Table I. All results have been corrected to sample collection time, and $^{210}$Po values have been corrected for ingrowth of $^{210}$Po from $^{210}$Pb between sample collection time and analysis where possible. Most of the results for gamma emitting radionuclides were below analytical detection limits and are not given in Table I.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Sampling period</th>
<th>Radioactivity concentration (wet) $^{(a)}$, Bq kg$^{-1}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$^{14}$C</td>
<td>$^{99}$Tc</td>
</tr>
<tr>
<td>Atlantic</td>
<td>July 2001</td>
<td>17 - 50</td>
<td>0.35 - 0.53</td>
</tr>
<tr>
<td>salmon</td>
<td>Oct - Dec 2001</td>
<td>10 - 15</td>
<td>0.24 - 0.42</td>
</tr>
<tr>
<td>Rainbow</td>
<td>July 2001</td>
<td>28 - 39</td>
<td>0.24 - 0.39</td>
</tr>
<tr>
<td>trout</td>
<td>Oct - Dec 2001</td>
<td>$&lt;16$ - 20</td>
<td>0.23 - 0.25</td>
</tr>
<tr>
<td>Salmon</td>
<td>July 2001</td>
<td>47 - 130</td>
<td>0.35 - 0.50</td>
</tr>
<tr>
<td>feed</td>
<td>Oct - Dec 2001</td>
<td>37 - 49</td>
<td>1.3</td>
</tr>
<tr>
<td>Trout</td>
<td>July 2001</td>
<td>64 - 110</td>
<td>$&lt;0.27$ - 0.44</td>
</tr>
<tr>
<td>feed</td>
<td>Oct - Dec 2001</td>
<td>30 - 36</td>
<td>0.36 - 0.58</td>
</tr>
</tbody>
</table>

$^{(a)}$ except for feed where dry concentrations apply

At about half of the farms, sampling was repeated after 3 to 4 months to check on variability of results. Examination of the data in Table I shows that there are differences between the radionuclide concentrations for the two sampling campaigns, but in general these are no more than a factor of about 4. There are larger differences, of an order of magnitude or more, for some of the $^{210}$Pb results. Taking the overall results of both sampling periods though, there are no significant differences between salmon and trout for the concentrations of a particular radionuclide.

The trout results showed no particular influence of water hardness on uptake of radioactivity from the fish feed. A comparison of the results for the organic fish farm with the conventional fish farm showed no particular differences between their radionuclide concentrations. Indeed, the results were consistent with those obtained at other salmon farms.

A small programme of monitoring salmon and trout is included in the broader FSA programme [1], and comparison of the results for gamma emitting radionuclides and $^{14}$C with this study shows broad consistency. Fish feed contains fishmeal, and the results in this study are consistent with gamma results for fishmeal in the FSA programme. Results for fishmeal were also reported in the earlier study.
[2], and the results for gamma emitting radionuclides, $^{14}$C, $^{99}$Tc and $^{210}$Po are consistent with those for fish feed in Table I.

There are no results for $^{210}$Pb and $^{210}$Po in salmon and trout in the routine FSA programme for comparison. However, a study [5] gave levels of natural radionuclides in seafood, including $^{210}$Po and $^{210}$Pb in cod, plaice and whiting sampled from around the English and Welsh coast during 1999. Concentrations of these radionuclides may be enhanced above natural levels as a result of anthropogenic sources, so sampling locations were chosen so as to avoid such sources, thereby providing results of natural concentrations. Concentrations of $^{210}$Pb and $^{210}$Po in marine fish ranged from 0.003 to 0.55 Bq kg$^{-1}$ and from 0.22 to 4.4 Bq kg$^{-1}$ respectively. The $^{210}$Pb values are comparable with those obtained for farmed fish in the present study, whereas the $^{210}$Po values are generally about an order of magnitude higher. However, both $^{210}$Pb and $^{210}$Po in farmed fish were at concentrations consistent with natural levels.

Table I also includes values for the $^{210}$Po / $^{210}$Pb quotients for samples since these enable consideration of whether $^{210}$Po and $^{210}$Pb are in equilibrium (i.e. the quotient has a value of 1 and $^{210}$Po is “supported” by $^{210}$Pb). A quotient of less than 1 would indicate $^{210}$Po has not equilibrated with its parent $^{210}$Pb, whereas a value greater than 1 would indicate a source of $^{210}$Po other than the $^{210}$Pb in the sample. For salmon fish feed, the quotients range from 3.1 to > 200, and for trout fish feed from 3.1 to 28. These results show that in the fish feed samples there was a source of $^{210}$Po other than the $^{210}$Pb they contained. For salmon, the quotients range from 0.13 to > 13, and for trout they range from 0.16 to > 29. For both salmon and trout, a number of the values were less than 1, and this is counter to the other study [5] which showed that $^{210}$Po in seafoods is largely unsupported by $^{210}$Pb. Indeed, the $^{210}$Po / $^{210}$Pb quotients for natural concentrations in fish [5] ranged from 3.5 to 240. It would appear that there are differences in the uptake and metabolism of $^{210}$Po by farmed fish and by wild sea fish which is possibly a reflection of their different diets.

No samples of salmon or trout were analysed for $^{99}$Tc in the FSA monitoring programme in 2001 [1]. However, some cod, plaice and whiting samples from the Irish Sea were analysed to monitor the effects of $^{99}$Tc discharges from Sellafield, and concentrations ranged from 0.75 to 64 Bq kg$^{-1}$. The single result for salmon (Table I) is lower than these results.

4. Dose assessments

Doses for hypothetical members of the public consuming farmed salmon and trout were assessed using the same procedures as those for the annual RIFE reports [1]. In essence, the individual dose (more formally ‘committed effective dose’) to a member of the public is calculated by the equation:

$$D_{ind} = \sum (C_R \times I_S \times DPUI_R)$$

where: $D_{ind}$ is the individual dose due to consumption of farmed fish (mSv y$^{-1}$), $C_R$ is the activity concentration of radionuclide R in farmed fish (Bq kg$^{-1}$), $I_S$ is the consumption rate for farmed fish (kg y$^{-1}$), and $DPUI_R$ is the dose per unit intake of radionuclide R (mSv Bq$^{-1}$).

For conservatism, the radionuclide concentrations used in the dose calculations were the maximum values of individual results obtained during the study. Thus, the values do not relate to any particular sample, but instead are for a sample assumed to have concentrations at the highest observed in the study. Although a number of the gamma emitting radionuclides were below analytical detection limits, these have been included, with the values being treated as positive ones at the limits of detection. In the case of $^{14}$C, $^{210}$Pb and $^{210}$Po, the measured concentrations may include both natural and anthropogenic sources. However, the assessments have been based on the total concentrations measured whatever the source, so again an element of conservatism has been introduced.
Dose calculations were carried out for adults, 15-year olds, 10-year olds and 1-year old infants consuming farmed fish at high rates and at average rates. A number of habits surveys undertaken by CEFAS have identified consumption of salmonids, and those at high (i.e. critical group) rates are used for assessments [1]. On the basis of these surveys, high and average salmon/trout consumption rates of 23 kg y\(^{-1}\) and 6.8 kg y\(^{-1}\) respectively were used for adults. For age groups other than adult, the adult rates were apportioned according to values given in [6]. For 15-year olds, 10-year olds and 1-year old infants, the high salmon/trout consumption rates used were 12 kg y\(^{-1}\), 12 kg y\(^{-1}\) and 8.6 kg y\(^{-1}\) respectively. The respective average consumption rates used were 2.9 kg y\(^{-1}\), 2.7 kg y\(^{-1}\) and 1.6 kg y\(^{-1}\). Dose per unit intake data were taken from [1] which are based on data from [7]. For \(^{210}\)Po, values appropriate to a gut transfer factor of 0.8 were used. Although current ICRP advice is that a factor of 0.5 is appropriate for dietary intakes of polonium [8], experimental evidence based on consumption of crabmeat suggests 0.8 would be more appropriate [9]. For conservatism, the higher value was chosen for consumption of farmed fish.

For high rate consumers of salmon/trout, the total assessed doses were 0.017, 0.014, 0.019 and 0.038 mSv y\(^{-1}\) for adults, 15 year olds, 10 year olds and 1-year old infants respectively. For average rate consumers, the total assessed doses were 0.0050, 0.0035, 0.0043 and 0.0070 mSv y\(^{-1}\) respectively. In each case, the main radionuclides contributing to dose were \(^{210}\)Po and \(^{210}\)Pb. Less than 10% of the doses were due to \(^{241}\)Am, less than 5% due to \(^{14}\)C and less than 5% due to the remaining radionuclides.

As previously noted, the concentrations of \(^{210}\)Po, \(^{210}\)Pb and \(^{14}\)C used in the assessments included both natural and anthropogenic sources. To enable assessment of only anthropogenic sources, a correction would need to be made for natural concentrations. If concentrations of \(^{14}\)C, \(^{210}\)Pb and \(^{210}\)Po typical of natural levels were assumed, the total doses would be more than halved with much of the remaining doses from \(^{210}\)Pb. However, since there is a large variation in natural concentrations of \(^{210}\)Pb, which makes it difficult to apportion values between natural or anthropogenic sources, doses as a result of anthropogenic sources could be trivial.

The significance of the assessed doses may be ascertained by comparison with the results of other assessments [1]. For example, doses to the UK public consuming diet at average rates in 2001 have been assessed as 0.15 mSv due to natural radionuclides (particularly \(^{210}\)Pb and \(^{210}\)Po) and 0.003 mSv from artificial radionuclides (particularly \(^{90}\)Sr and \(^{35}\)S). For high rate seafood consumers around Sellafield in 2001, doses were 0.16 mSv due to artificial radionuclides (particularly \(^{239/240}\)Pu and \(^{241}\)Am) with an additional 0.43 mSv due to natural radionuclides (particularly \(^{210}\)Pb and \(^{210}\)Po) enhanced above natural concentrations. For the UK public, the average dose rates from all sources have been assessed as 2.6 mSv y\(^{-1}\) with natural sources contributing 2.2 mSv y\(^{-1}\) [10]. The assessed doses from farmed fish are lower than in all these examples. The doses may also be compared with the EU limit for members of the public of 1 mSv, noting that this limit applies to controlled releases of radionuclides (anthropogenic and natural) from artificial sources. Again, the assessed doses are considerably lower than this limit.

5. Transfer factors

Transfer factors are used in models to enable evaluation of radionuclide transfer from animal diet (e.g. feed) to animal produce (e.g. meat or milk). Commonly, they are expressed as the ratio of the radionuclide concentration in produce (Bq kg\(^{-1}\)) (at equilibrium or at time of slaughter) to the daily intake of radioactivity (Bq d\(^{-1}\)). For this study, calculations were carried out for farmed fish using:

\[
TF = \frac{C_R}{C_{FF} \times I_D}
\]

where:  
TF is the transfer factor (d kg\(^{-1}\)),  
\(C_R\) is the activity concentration of radionuclide R in farmed fish (Bq kg\(^{-1}\)),  
\(C_{FF}\) is the activity concentration of radionuclide R in fish feed (Bq kg\(^{-1}\)), and  
\(I_D\) is the daily intake of fish feed (kg d\(^{-1}\)).
Farmed fish change their daily intake of feed according to species, size and water temperature. Typically though, feeding rates range from 0.7 to 1.2 % body weight per day for both salmon and trout. An average value of 1% was chosen for the calculations and since trout and salmon in this study were typically 0.25 kg and 4 kg respectively, the values of $I_0$ used were $2.5 \times 10^{-3}$ kg d$^{-1}$ for trout and $4 \times 10^{-5}$ kg d$^{-1}$ for salmon. Transfer factors were evaluated for each fish sample and its corresponding fish feed sample using measured radionuclide concentrations. For salmon, the values range from 3.3 to 23 d kg$^{-1}$ for $^{14}$C, from 12 to >33 d kg$^{-1}$ for $^{137}$Cs, from <0.23 to 4.4 d kg$^{-1}$ for $^{210}$Pb and from 0.079 to 0.59 d kg$^{-1}$ for $^{210}$Po. For $^{99}$Tc, the single value for salmon was 4.8 d kg$^{-1}$. For trout, the values range from 100 to 230 d kg$^{-1}$ for $^{14}$C, from 170 to >370 d kg$^{-1}$ for $^{137}$Cs, from <2.8 to 48 d kg$^{-1}$ for $^{210}$Pb and from 2.4 to 13 d kg$^{-1}$ for $^{210}$Po. It can be seen that there are distinct differences for the transfer factors for salmon and trout, with the latter having much higher values.

The relative concentrations of radionuclides in fish and fish feed can be used to provide some insights into transfer mechanisms. Approximately 5 kg fish is used to produce 1 kg fishmeal and fish feed contains approximately 50% fishmeal. Therefore, if it were assumed that farmed fish reached the same radionuclide concentration as the fish making up the fishmeal in the fish feed (i.e there was no biomagnification or depletion of radioactivity from fishmeal to fish), the relationship between radionuclide concentrations in fish and fish feed becomes:

$$\frac{C_R}{C_{FF}} = 0.4$$

Values of this ratio were calculated for samples from each fish farm and the results are summarised as ranges and median values in Table II. Ratios for a farm which were “less than” or “greater than” were excluded from the calculation of median values.

<table>
<thead>
<tr>
<th></th>
<th>Atlantic salmon</th>
<th>Rainbow trout</th>
<th>Salmon / trout</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C</td>
<td>range</td>
<td>0.13 - 0.91</td>
<td>&lt;0.52 - 0.56</td>
</tr>
<tr>
<td></td>
<td>median</td>
<td>0.34</td>
<td>0.47</td>
</tr>
<tr>
<td>$^{99}$Tc</td>
<td>range</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>range</td>
<td>0.49 - &gt;1.3</td>
<td>0.43 - &gt;0.93</td>
</tr>
<tr>
<td></td>
<td>median</td>
<td>0.82</td>
<td>0.56</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>range</td>
<td>&lt;0.0093 - 0.17</td>
<td>&lt;0.0070 - 0.12</td>
</tr>
<tr>
<td></td>
<td>median</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>$^{210}$Po</td>
<td>range</td>
<td>0.0031 - 0.024</td>
<td>0.0061 - 0.033</td>
</tr>
<tr>
<td></td>
<td>median</td>
<td>0.0068</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Since the median values for $^{14}$C are similar to the value of 0.4, it would imply that no biomagnification or depletion has taken place. For $^{137}$Cs however, the median ratios are greater than 0.4 which would suggest that some biomagnification has taken place. For $^{99}$Tc, $^{210}$Pb and $^{210}$Po, with ratios lower than 0.4, there would appear to be depletion between fish feed and salmon and trout.

6. Acknowledgements

This work was funded by the FSA as project R02015, and a number of people in the farmed fish industry helped by providing samples and information. It is with pleasure that thanks are recorded here for this assistance.

7. References


